Lunar Global Heat Flow: Predictions and Constraints

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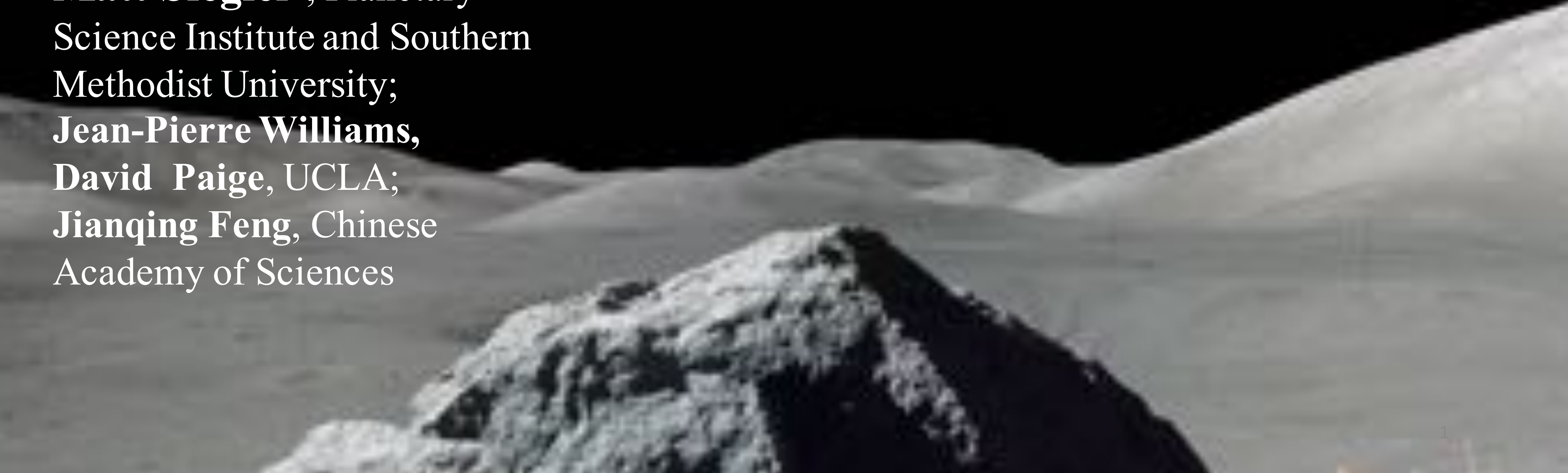
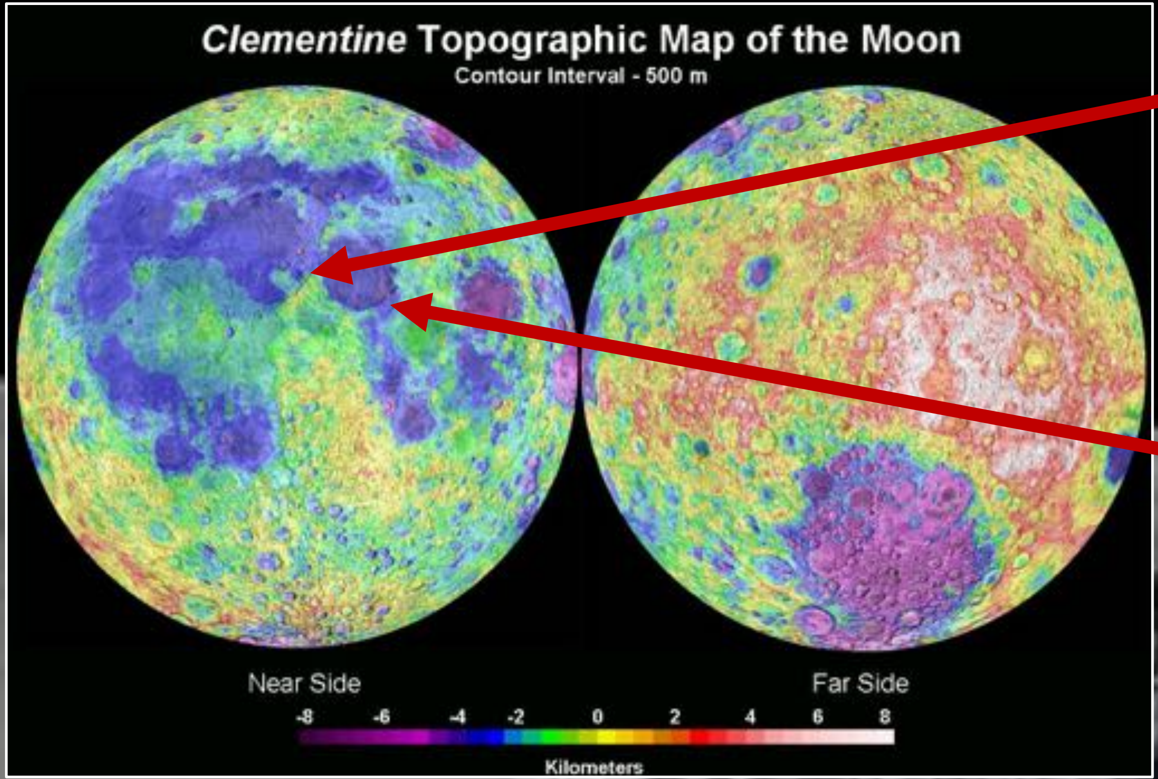
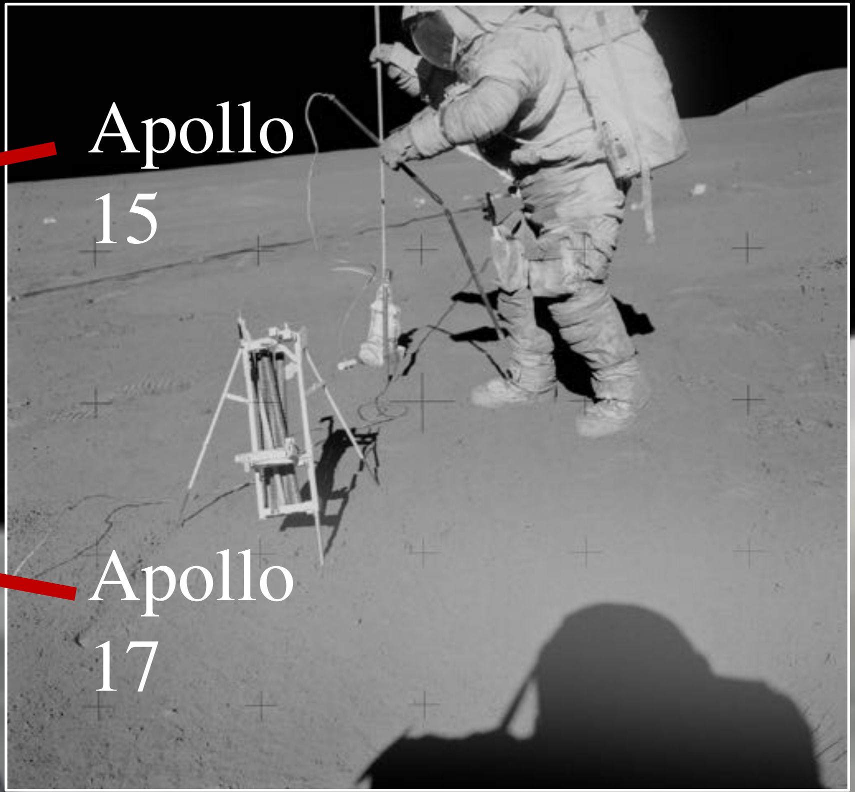


Conceptual Overview:

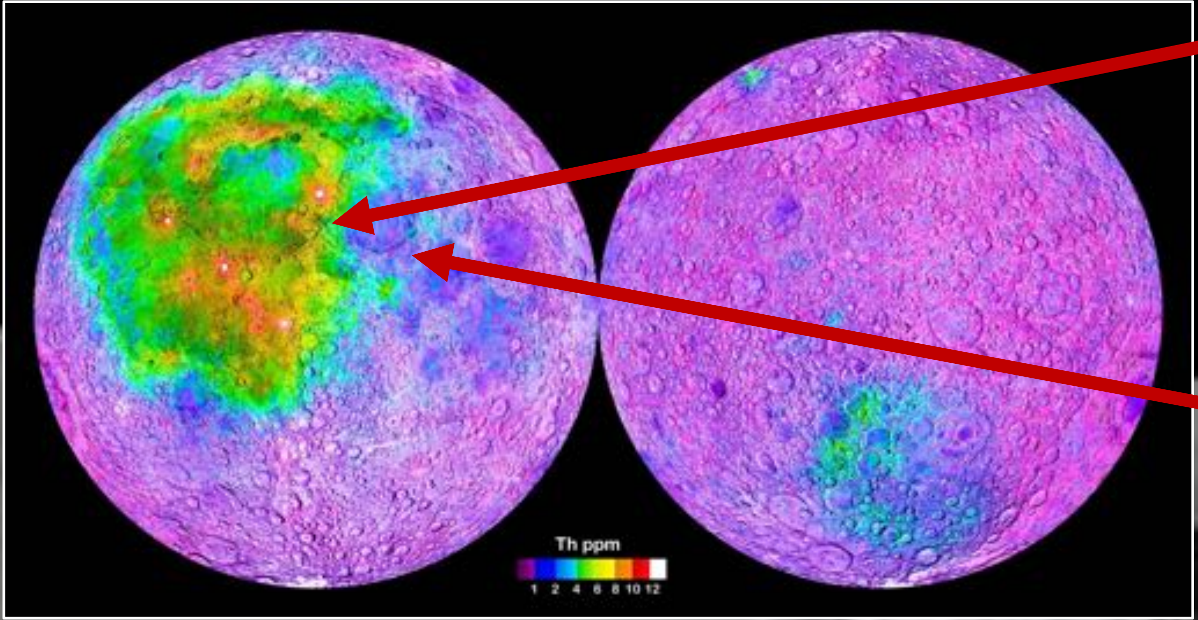
- We have 2 heat flow data points for the Moon from Apollo 15 and 17
- At least they are representative… right?

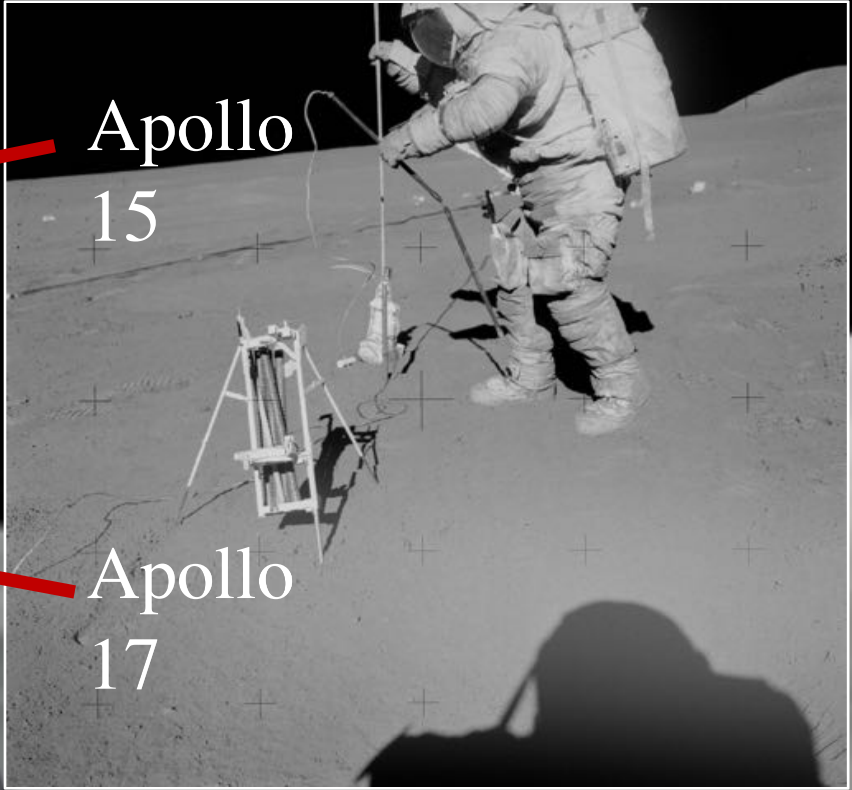




Conceptual Overview:

- Unfortunately, the two locations were at the boundary of the largest heat producing anomaly on the Moon, the Thorium-rich Procellarum KREEP Terrain (PKT)



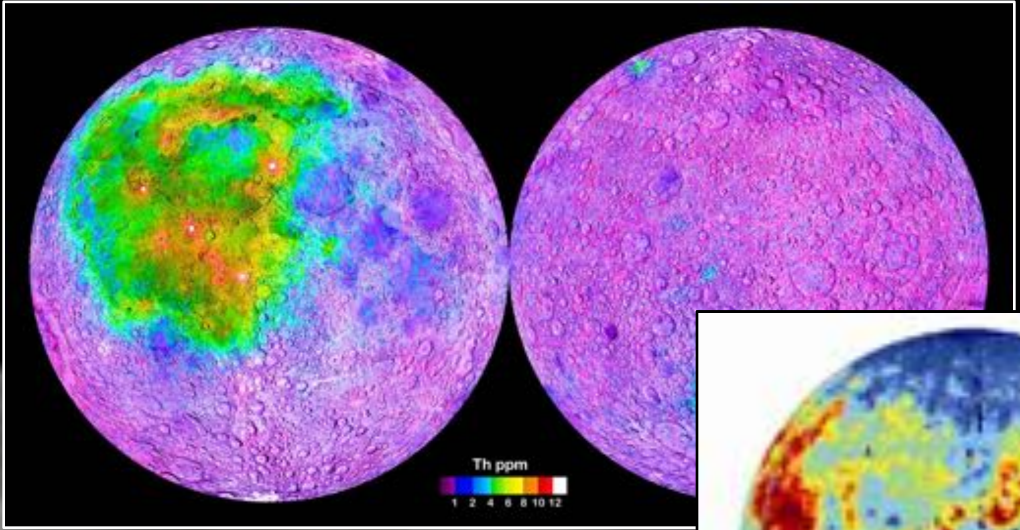


Really guys?? That is where you put them?!?

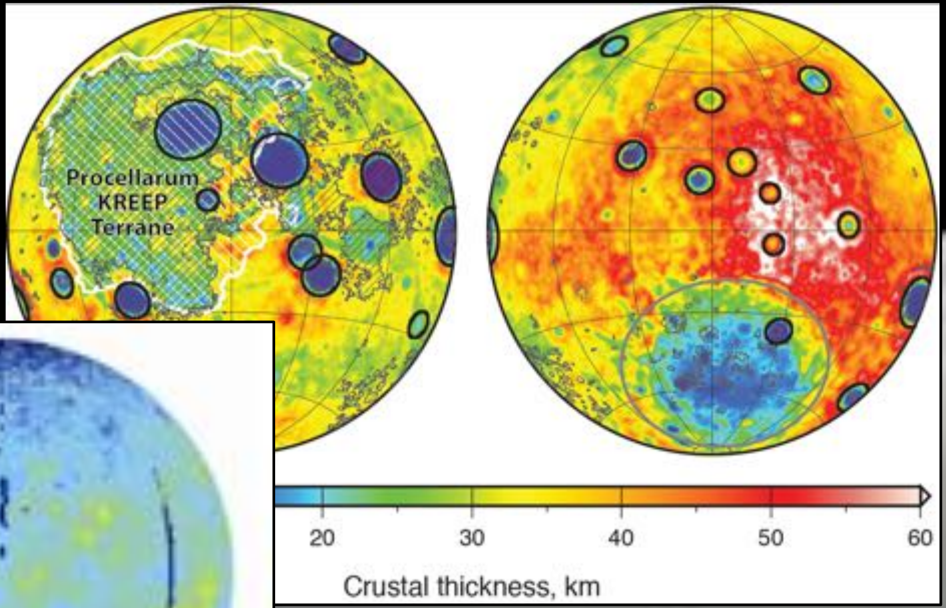
(In their defense, we didn't know about the PKT yet… and they were super cool places to land)

Conceptual Overview:

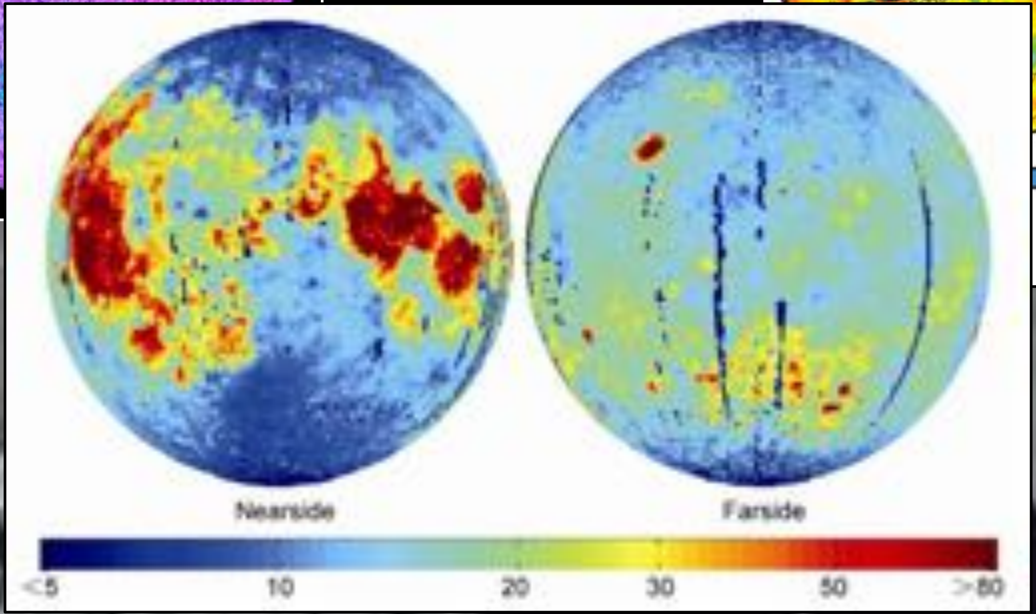
- The Apollo data is obviously anomalous
- With the new data we have (Lunar Prospector, GRAIL, Chang’E,…) can we use the Apollo data to constrain global heat production?



e.g., Lawrence et al., 2000, 2003



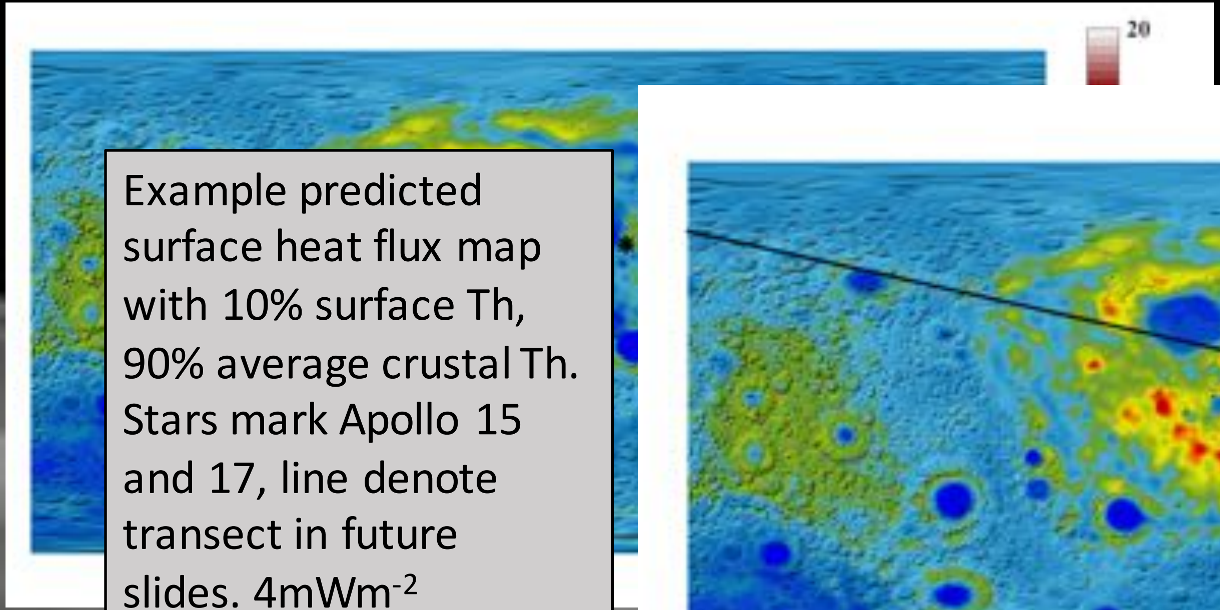
e.g,. Wieczorek et al., 2012

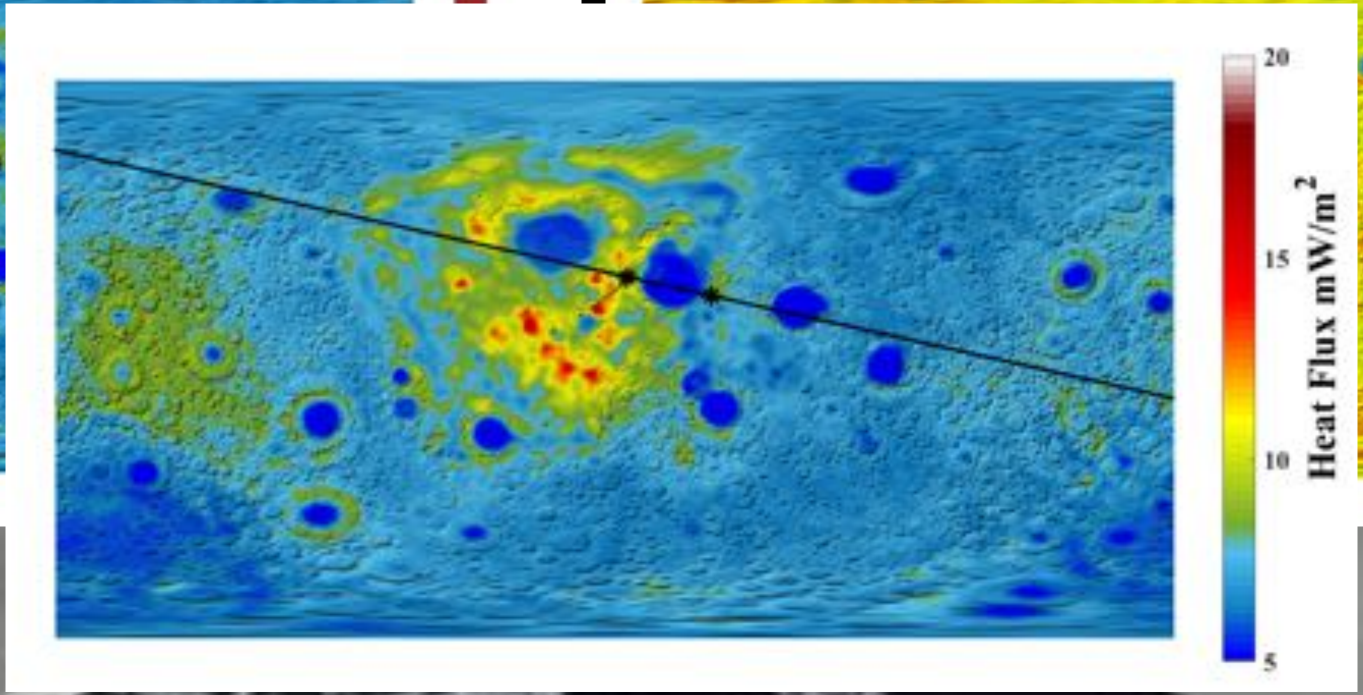


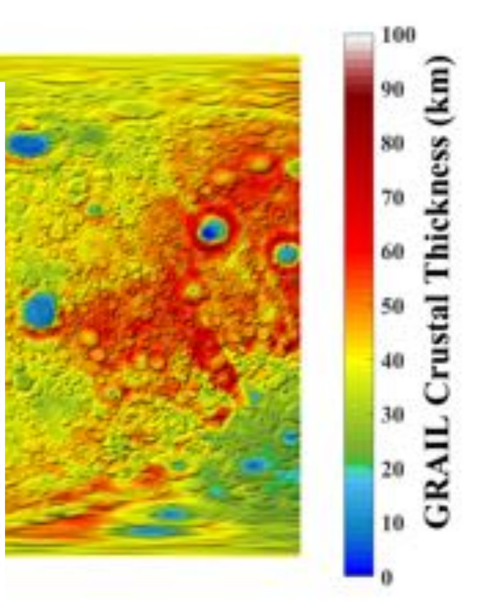
e.g., Fa et al., 2010

Model Basics

- Here we take Lunar Prospector Th and GRAIL crustal thickness and model plausible crustal radiogenic compositions assuming x% surface Th, y% average crustal Th (with proportional U and K)
- Thin crust and low Th areas show low heat flux, Stars mark Apollo 15 and 17 sites



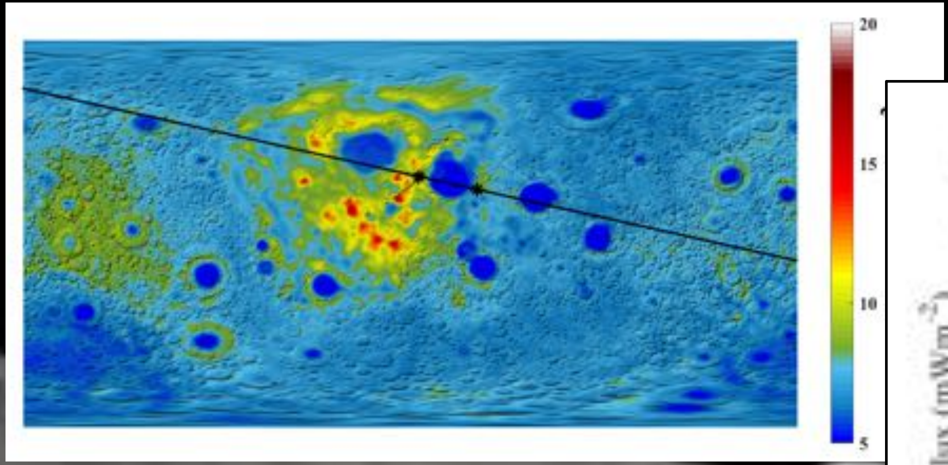


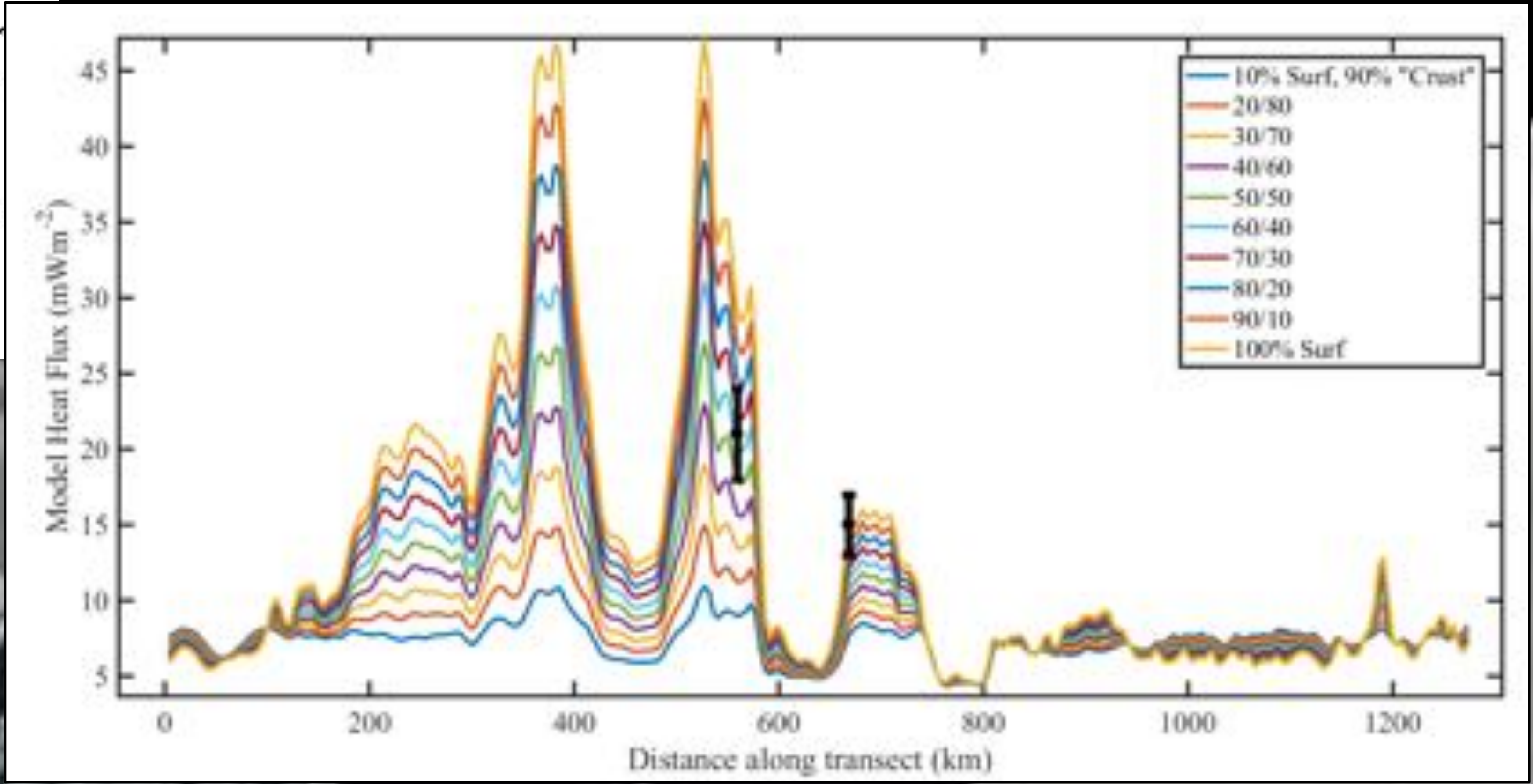


Example predicted surface heat flux map with 10% surface Th, 90% average crustal Th. Stars mark Apollo 15 and 17, line denote transect in future slides. 4mWm^{-2} assumed from mantle heat production.

Transects:

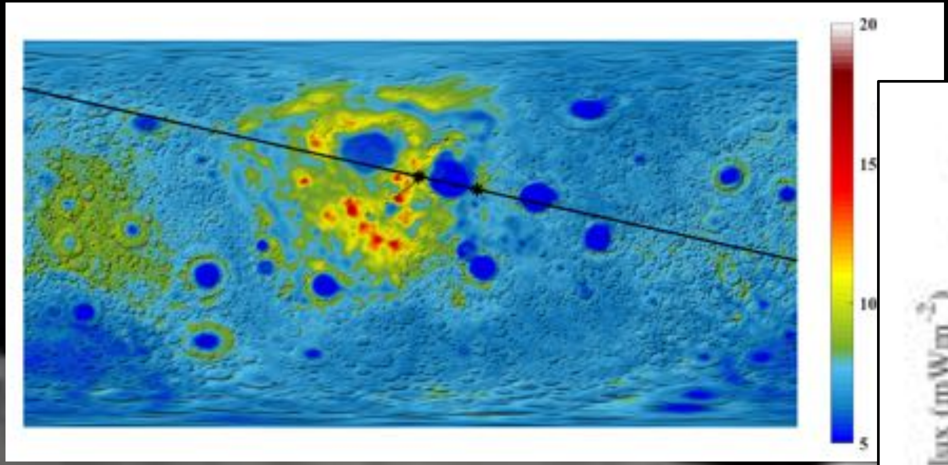
- We can look at modeled heat flux values across a transect through the two Apollo sites (similar to Siegler and Smrekar, 2014) to constrain plausible radiogenic distribution

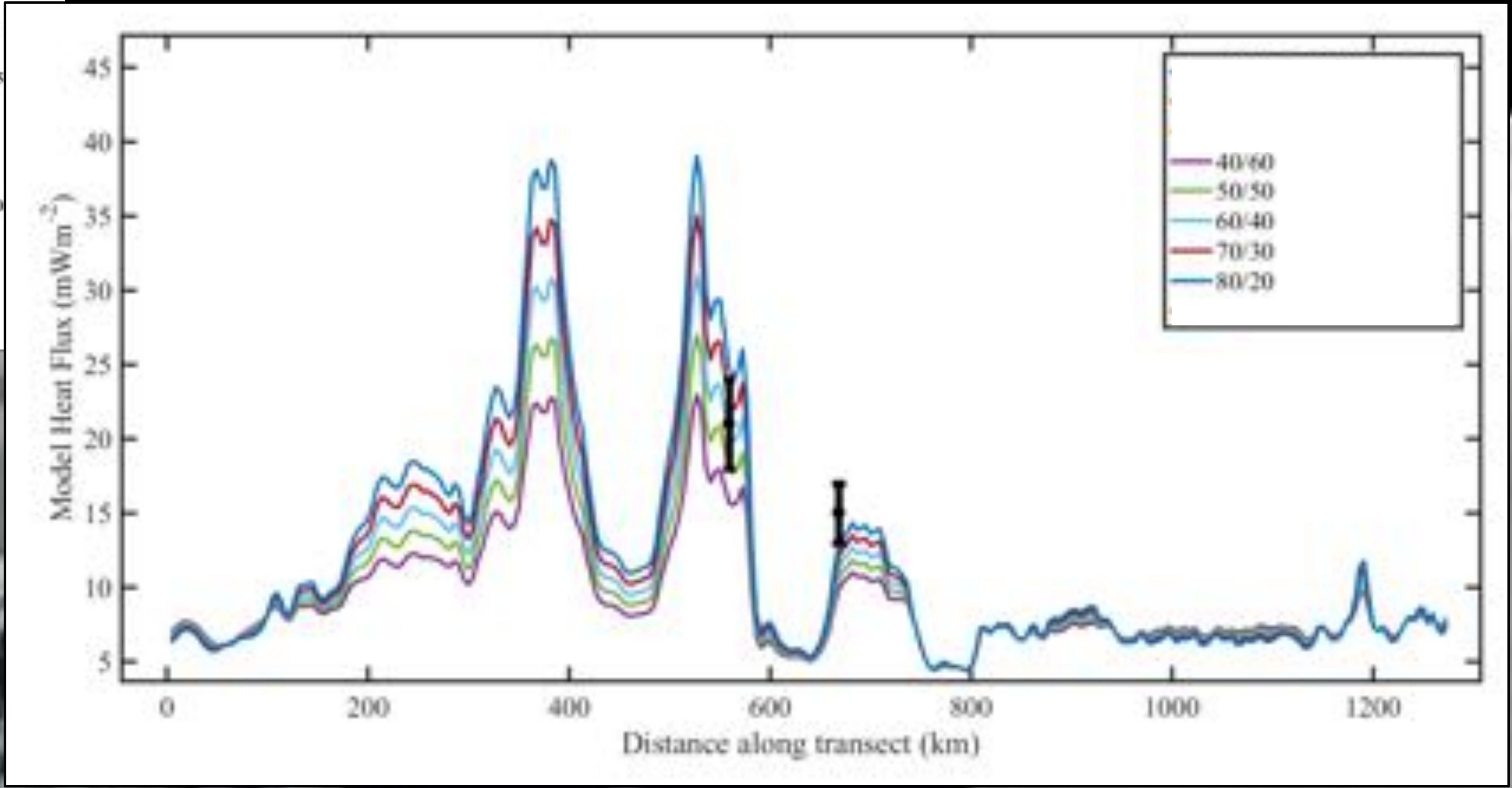




Transects:

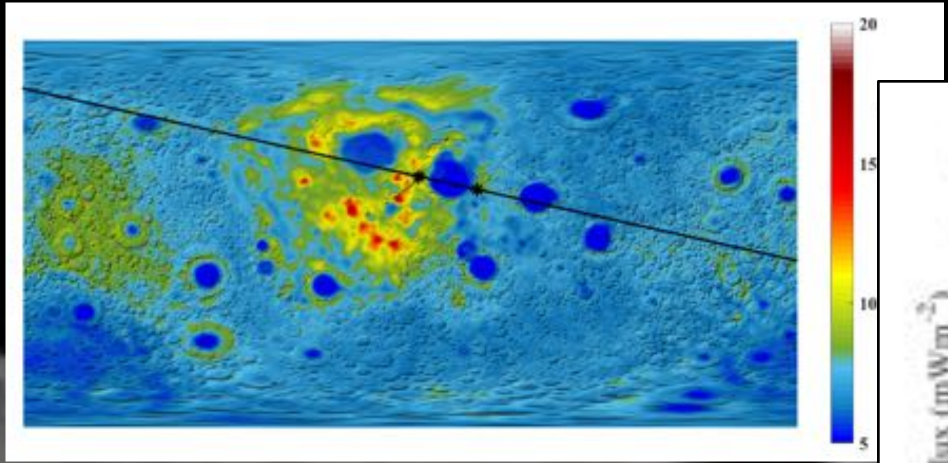
- Removing models not consistent with Apollo 15, we can see this simple model is hard to make consistent with Apollo 17 within reported error (Langseth et al., 1976)
- This either means there is more KREEP within or under the crust or more mantle heat production than out 4mWm^{-2} assumption.

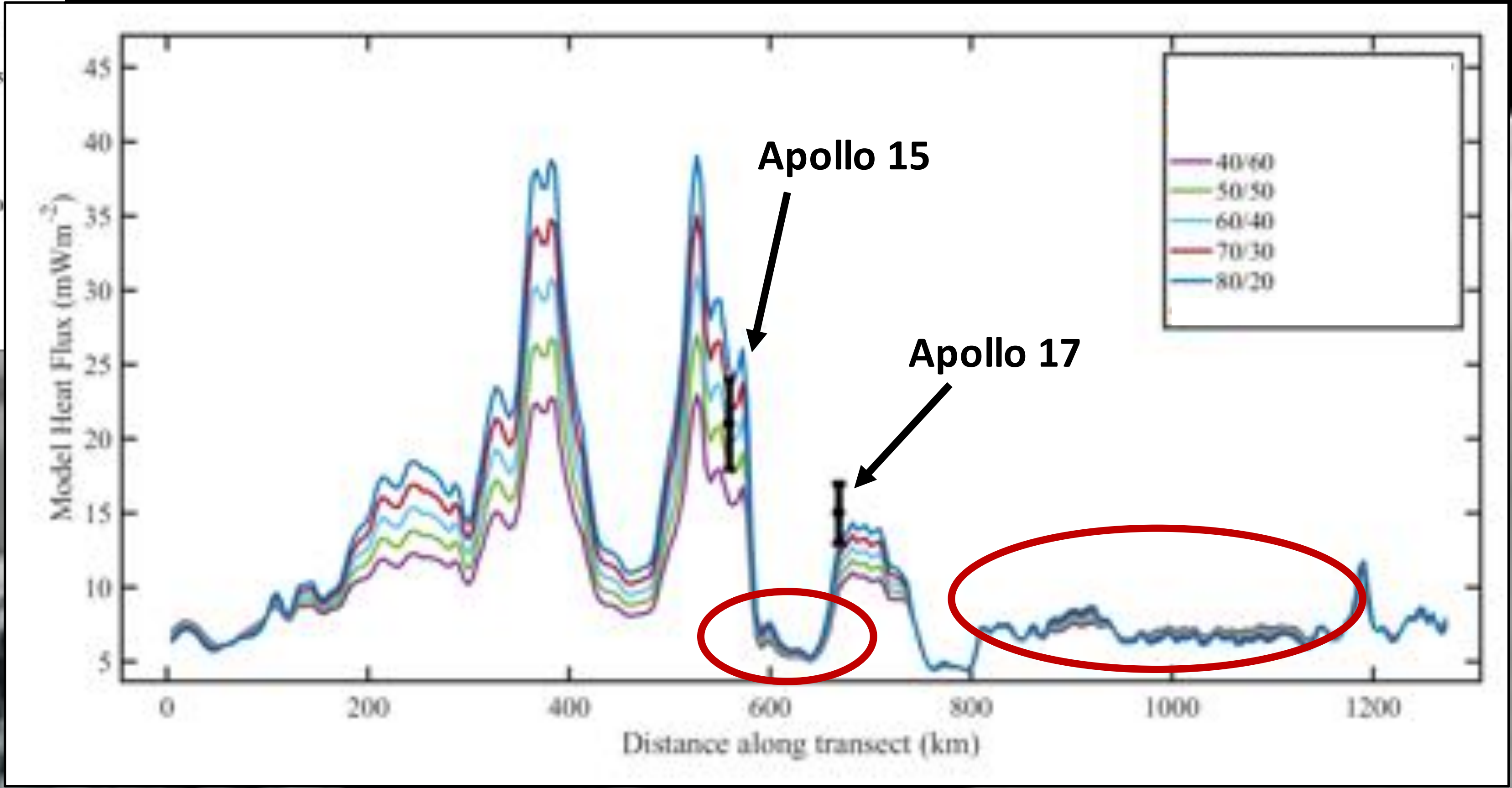




Transects:

- We can also see that the Apollo sites were in areas where unknown crustal radiogenic distributions would make large differences.
- Low thorium areas (in Serenitatis or on the far side for instance) are more sensitive to the mantle contribution to the heat flux and insensitive to surface contribution.



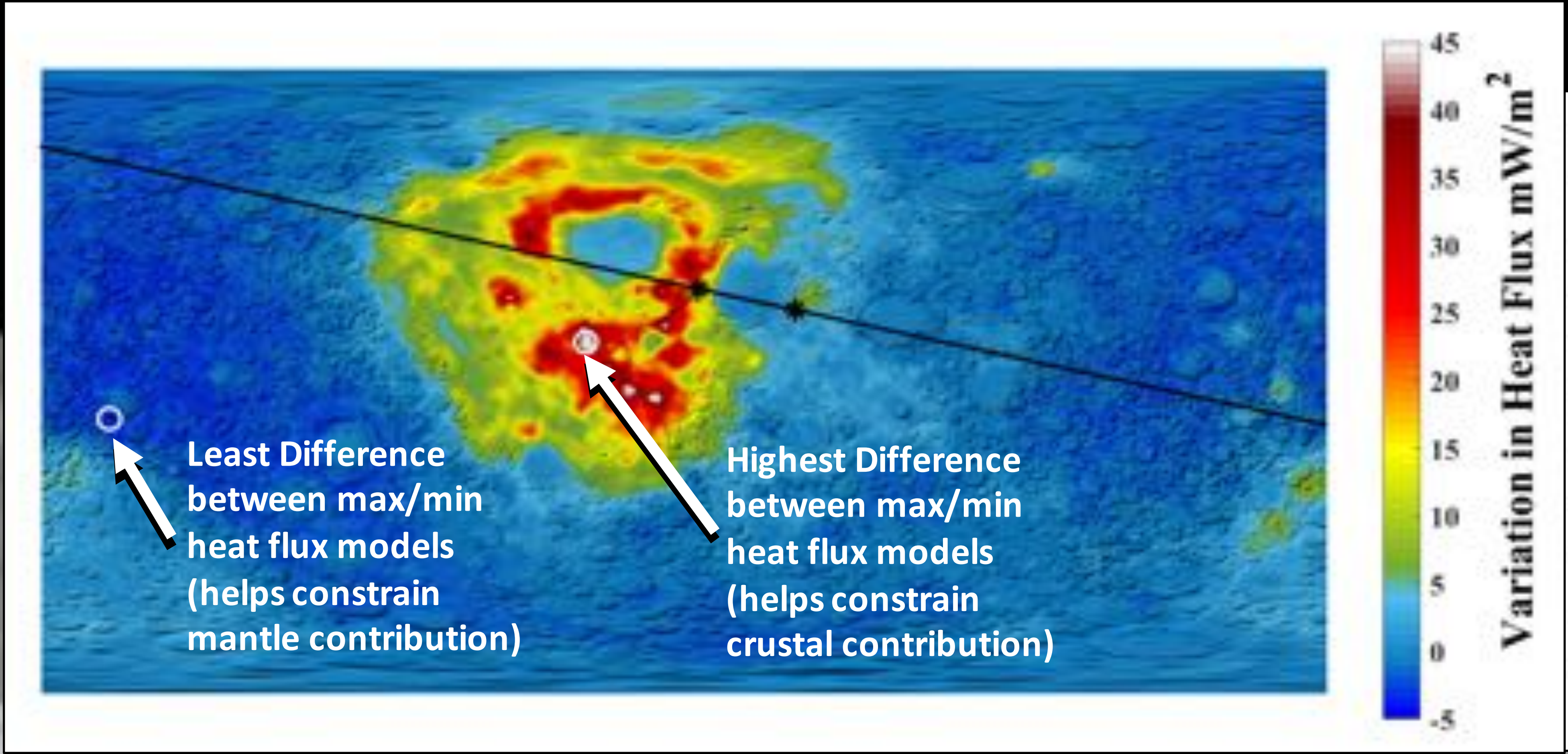


Where to land?:

- There is also some variation in GRAIL derived crustal thickness and density (from M. Wieczorek website) that adds uncertainty.

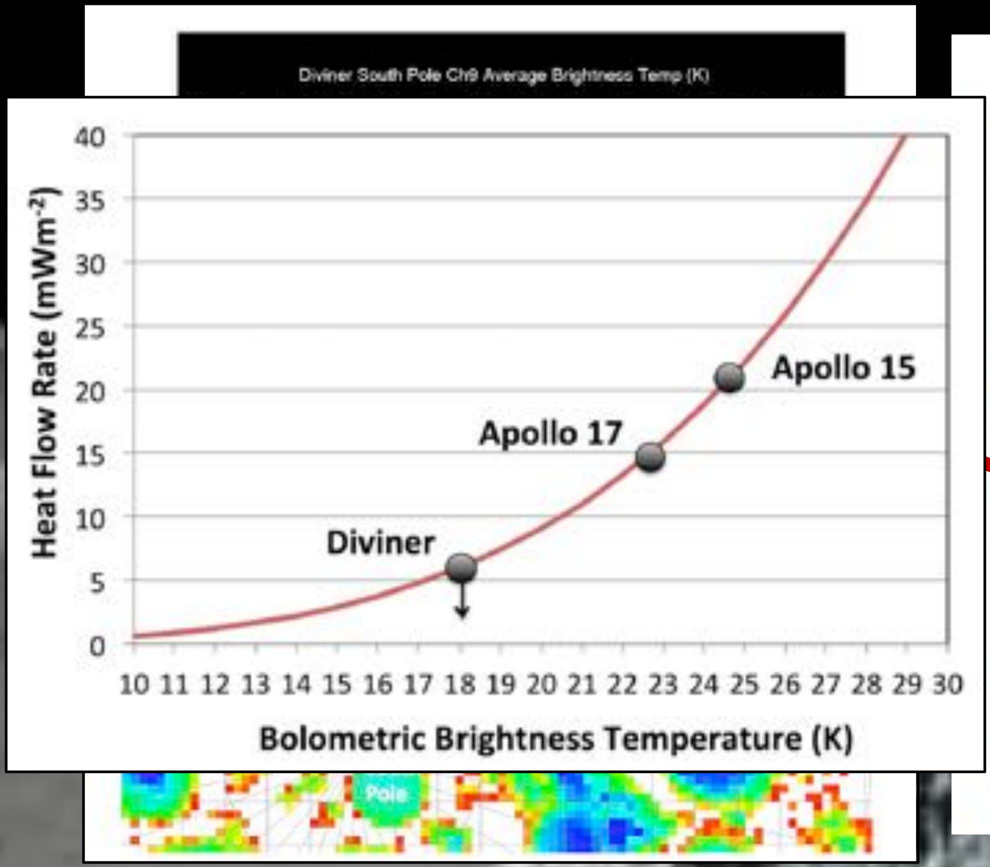
Model	Average thickness (km)	Minimum thickness (km)	Apollo 12/14 thickness (km)	ϕ (%)	ρ_m (kg m^{-3})	λ
1	34	0.6	29.9	12	3220	80
2	35	0.2	30.8	7	3360	80
3	43	1.0	38.1	12	3150	70
4	43	0.5	38.0	7	3300	70

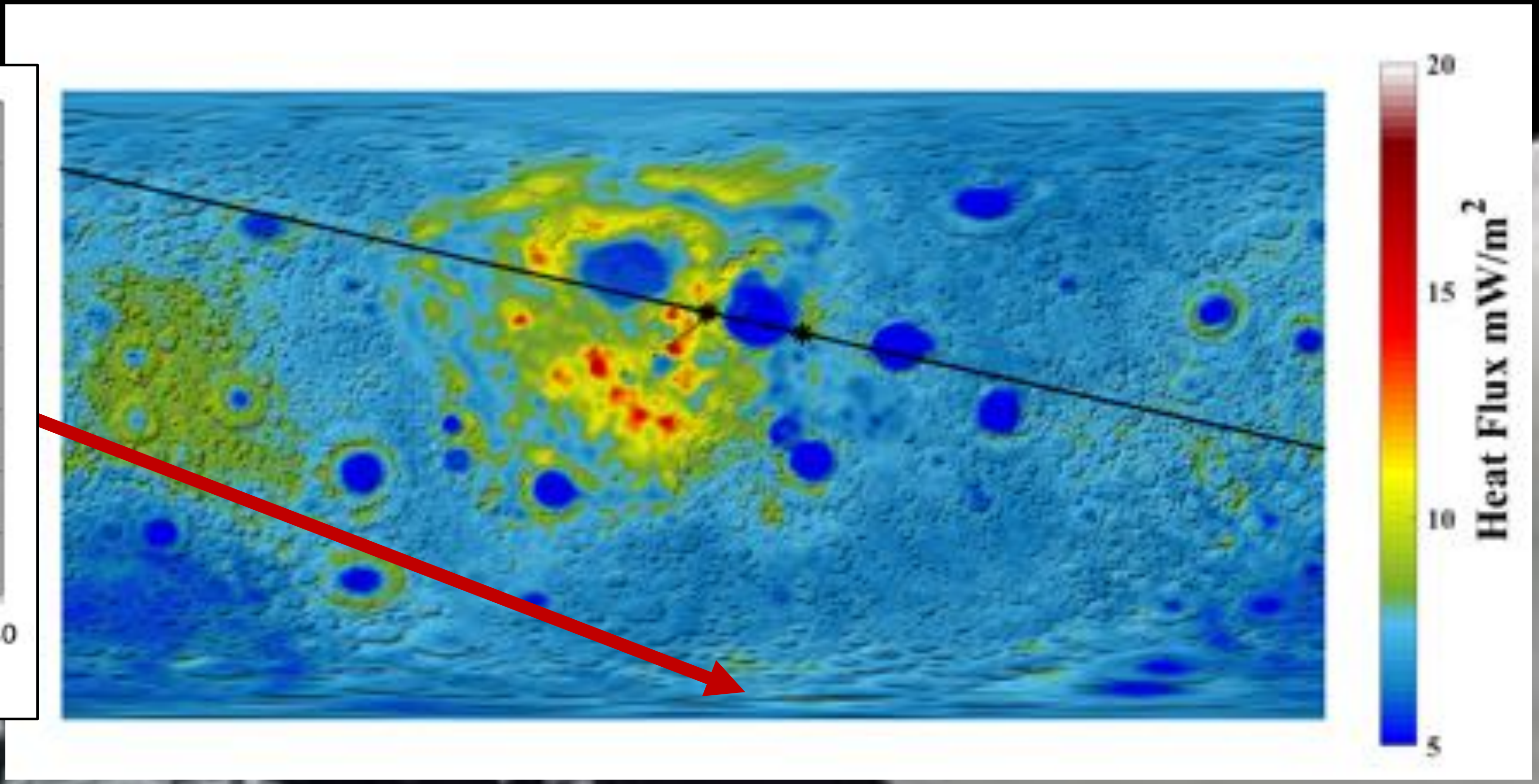
- We can map this uncertainty to quantify where a heat flux measurement would be most helpful to pin down a global heat flux model.



Can other data sets help?:

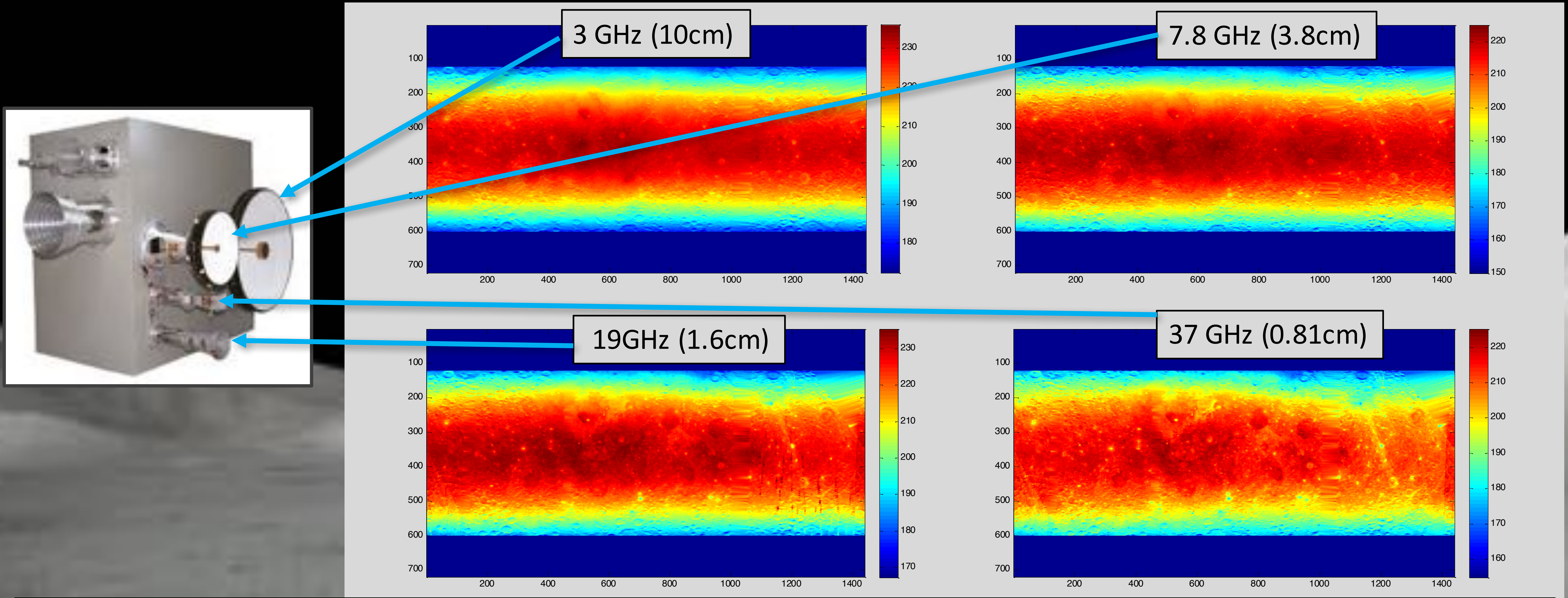
- We (Dave Paige and I) have presented (and are finally publishing) new constraint from LRO's Diviner of a cold crater near the south pole that reaches ~18K in winter.
- This should provide an upper limit on the heat flux in an area far from PKT and potentially provide a better constraint on mantle heat flux seems consistent with model predictions.





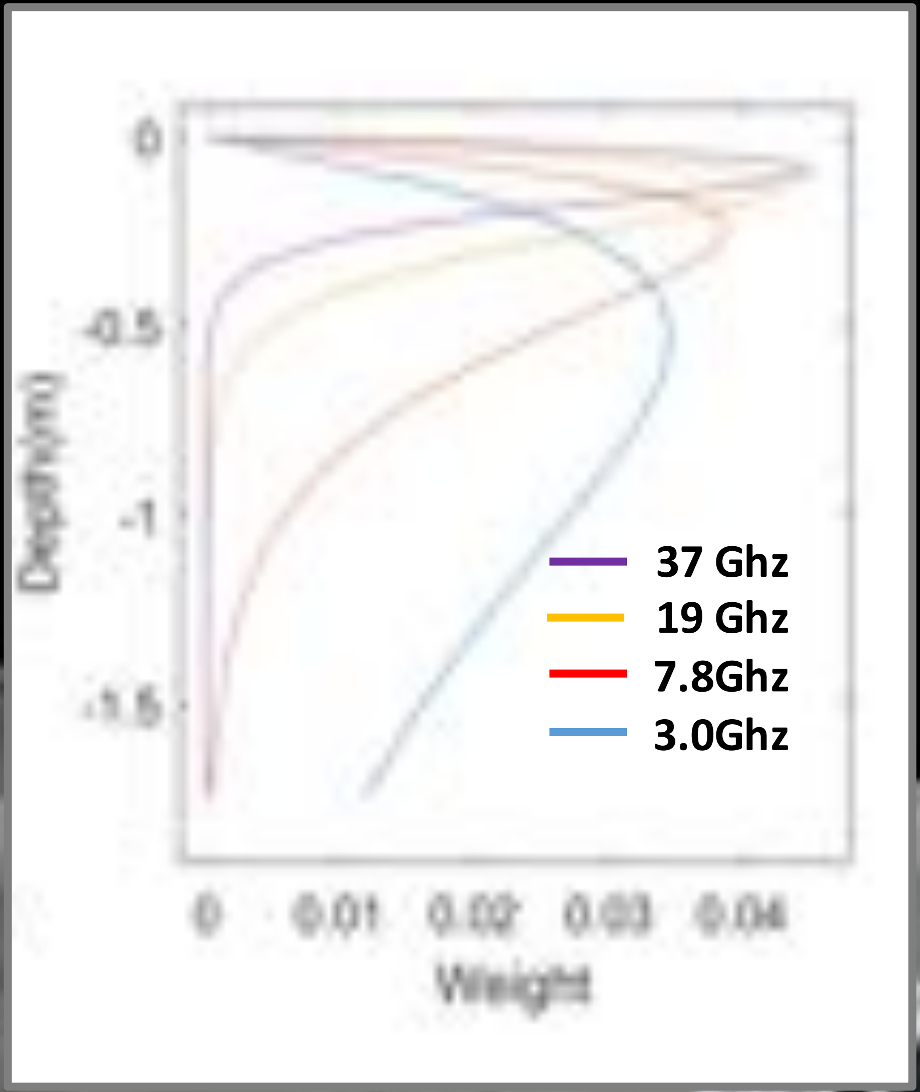
Can other data sets help?

- Another exciting potentially useful data set is the Chang'E 2 Microwave Radiometer (MRM), which was a 4 channel microwave radiometer.



Microwave radiometers are in common use for atmospheric temperature sounding (Earth-orbting MLS mission, Juno MWR instrument). Here we are simply using the same idea with the 4 channel Chang'E MRM for regolith temperature sounding.

Chang'E Constraints?



$$w_i = (1 \quad s_i)\ (1 \quad e^{\ 2k_i d_i})\ (1+\left|R_{i(i+1)}\right|^2 \quad e^{\ 2k_i d_i}) \quad \sum_{j=0}^{i\ \ 1} ((1 \quad \left|R_{j(j+1)}\right|^2)\ \ e^{\ 2k_j d_j})$$

Where wi is the weight coefficient of layer i,

Si is the single scattering albedo in layer i

ki is the absorption coefficient of layer i

$$k_i = 2 \quad \frac{f}{c} \sqrt{\quad} \tan$$

"Loss tangent"

$R_{i(i+1)}$ is the reflection coefficient between layer i and layer i+1

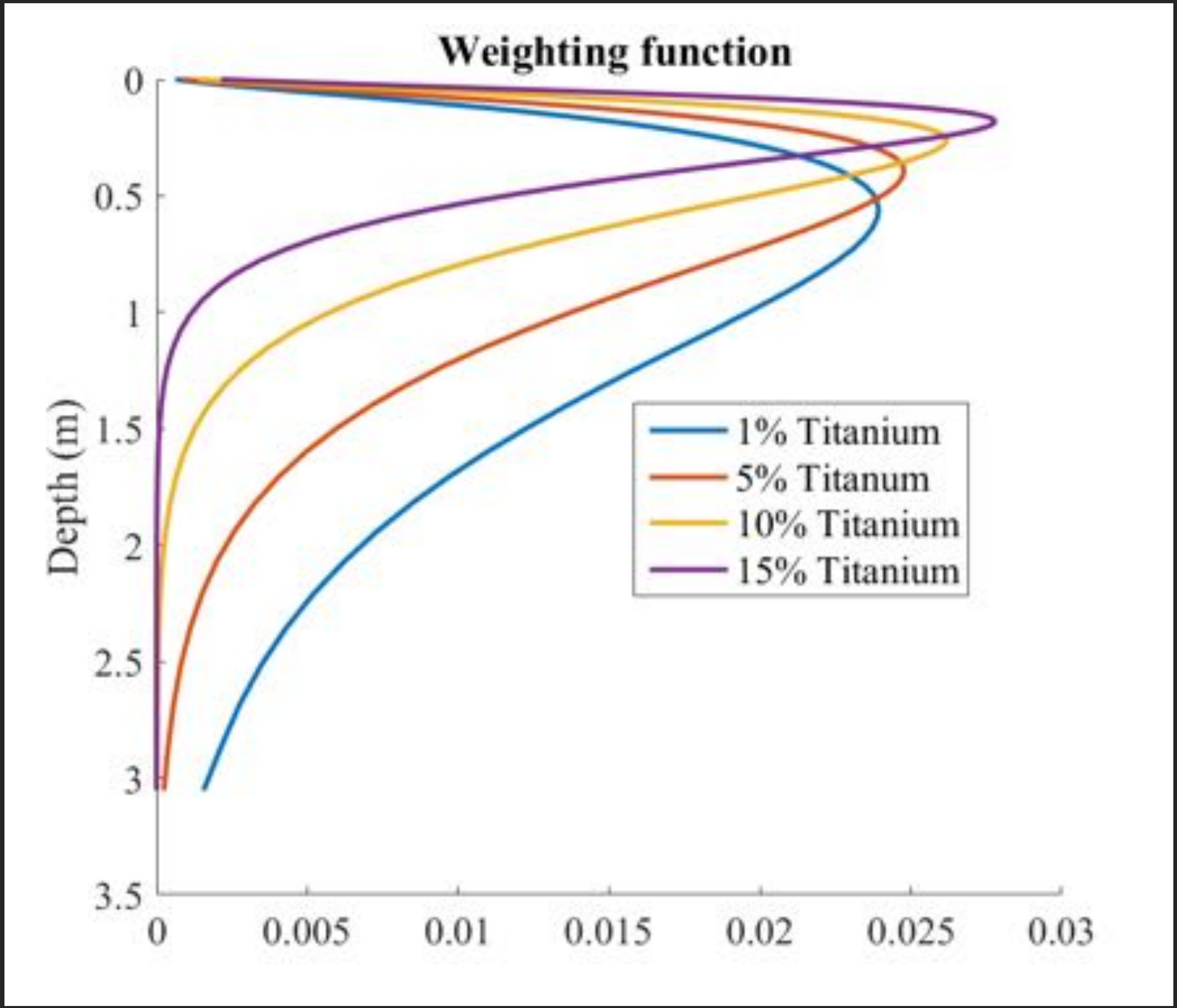
$$R_{i(i+1)} = \frac{\sqrt{\quad_{i+1}} \quad \sqrt{\quad_i}}{\sqrt{\quad_{i+1}} + \sqrt{\quad_i}}$$

The <u>Brightness Temperature</u>, *TB* is simply:

$$TB = \Sigma\ T_i w_i$$

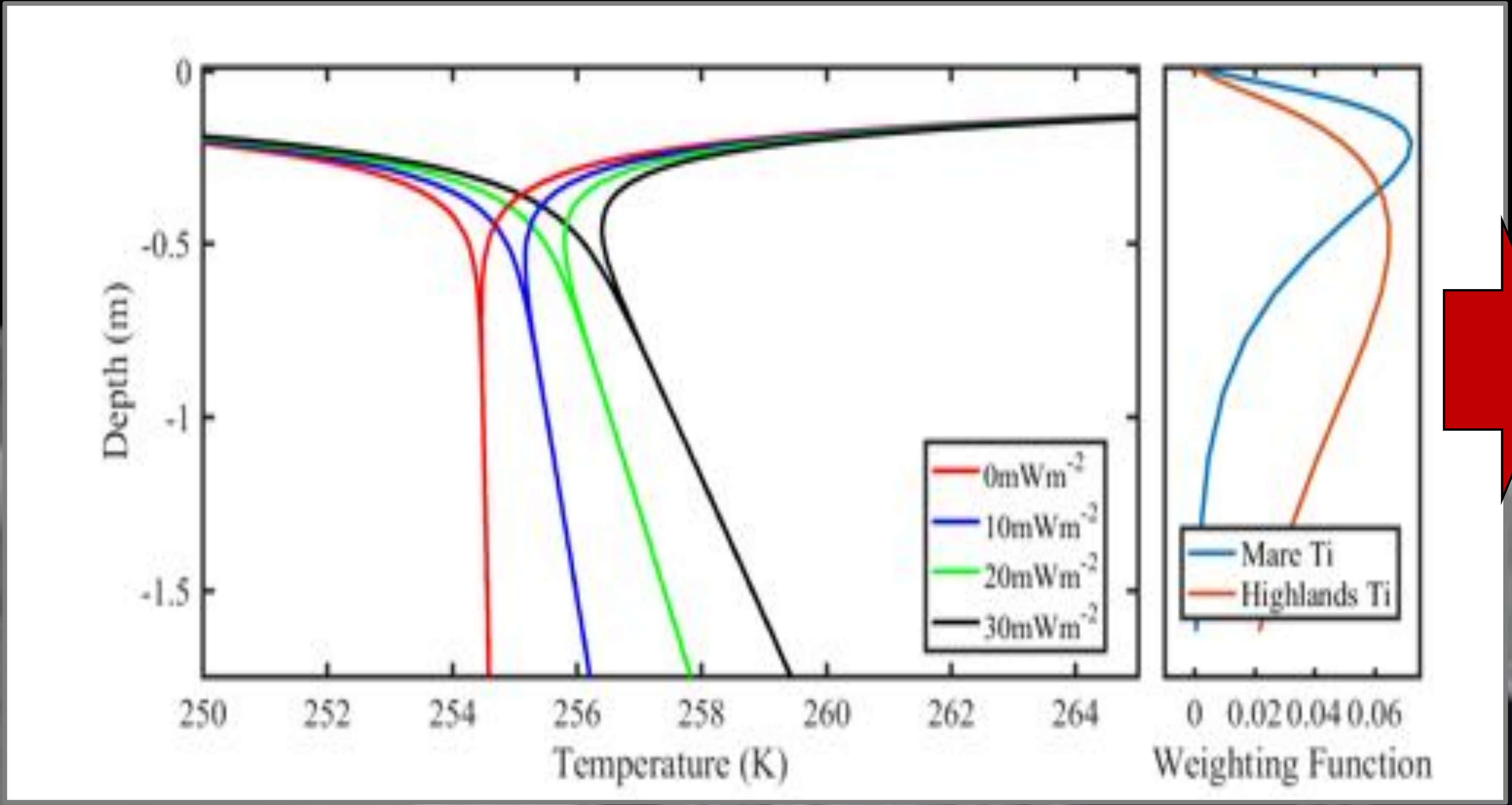
Chang'E Constraints?

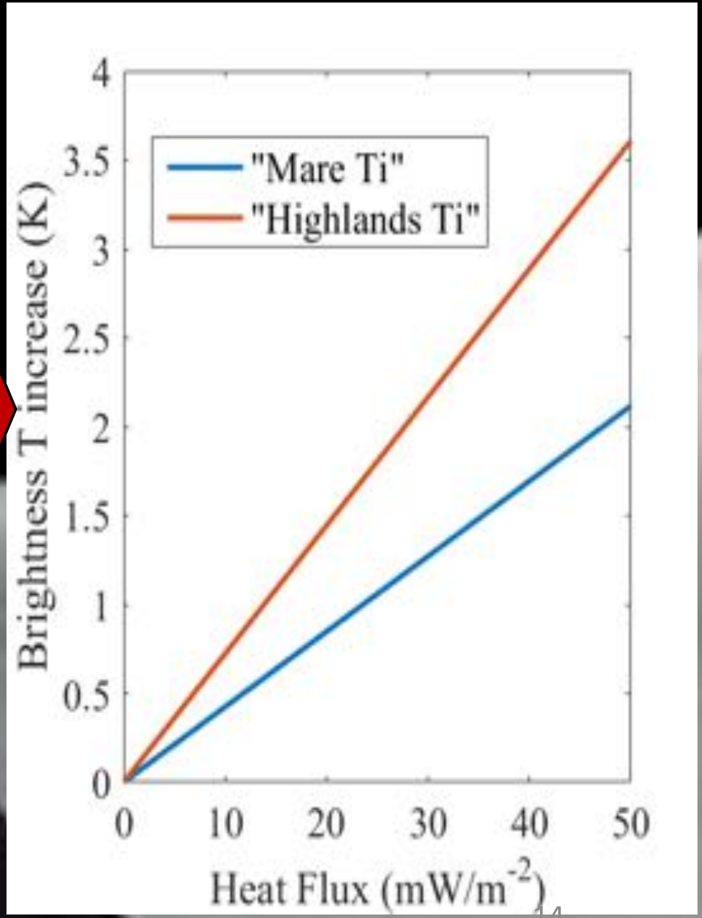
- The loss tangent is highly dependent on the amount of Titanium in the regolith.
- But in areas of low Titanium, the 3Ghz MRM channel (10cm wavelength) is getting a considerable amount of radiation from up to ~3m depth.



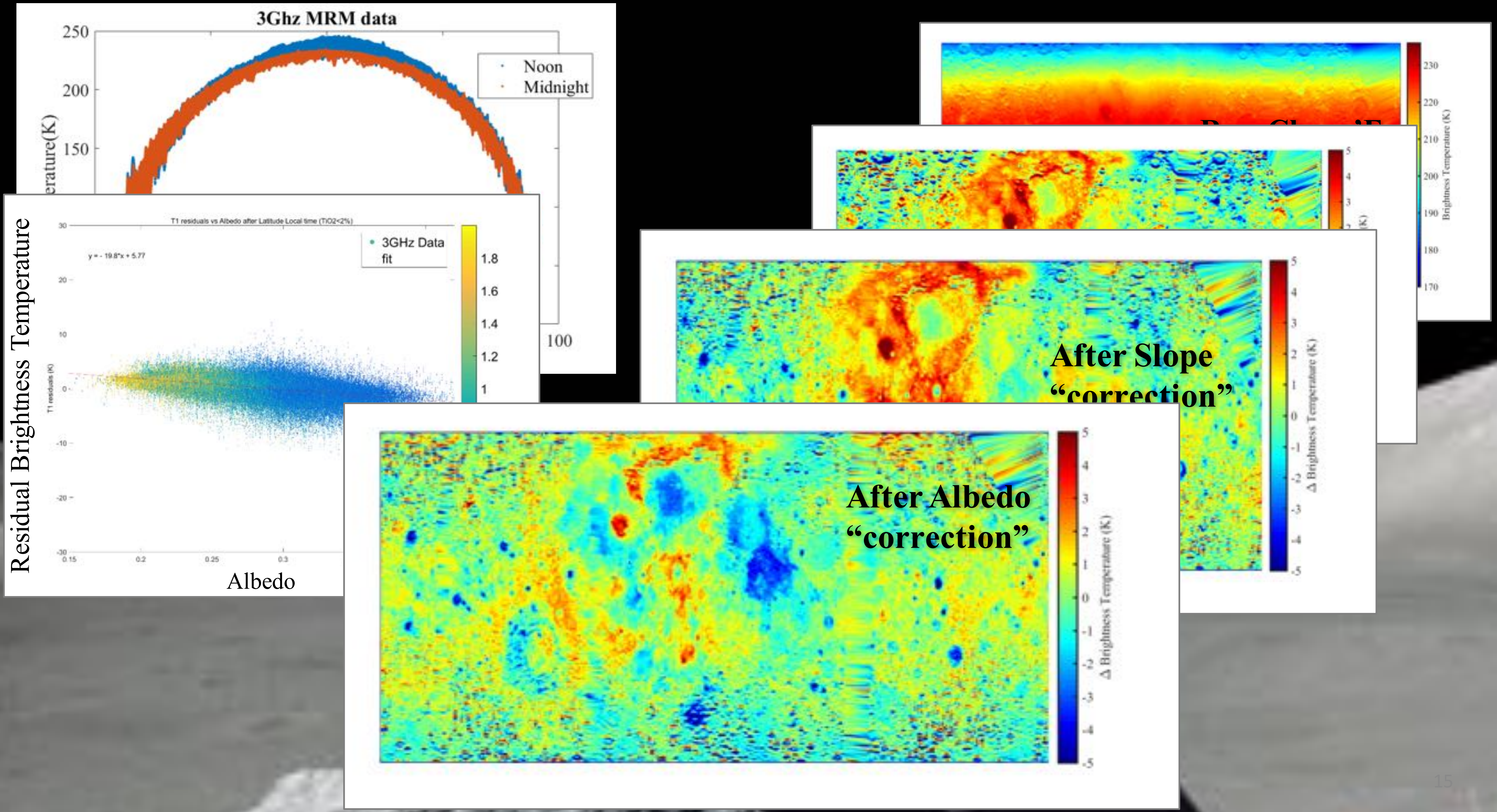
Chang'E Constraints?

We then can calculate Diviner constrained subsurface temperature models for various geothermal heat fluxes to create a model of Brightness Temperature vas a function of geothermal heat flux. So higher TB means you are seeing deeper or higher heat flux.

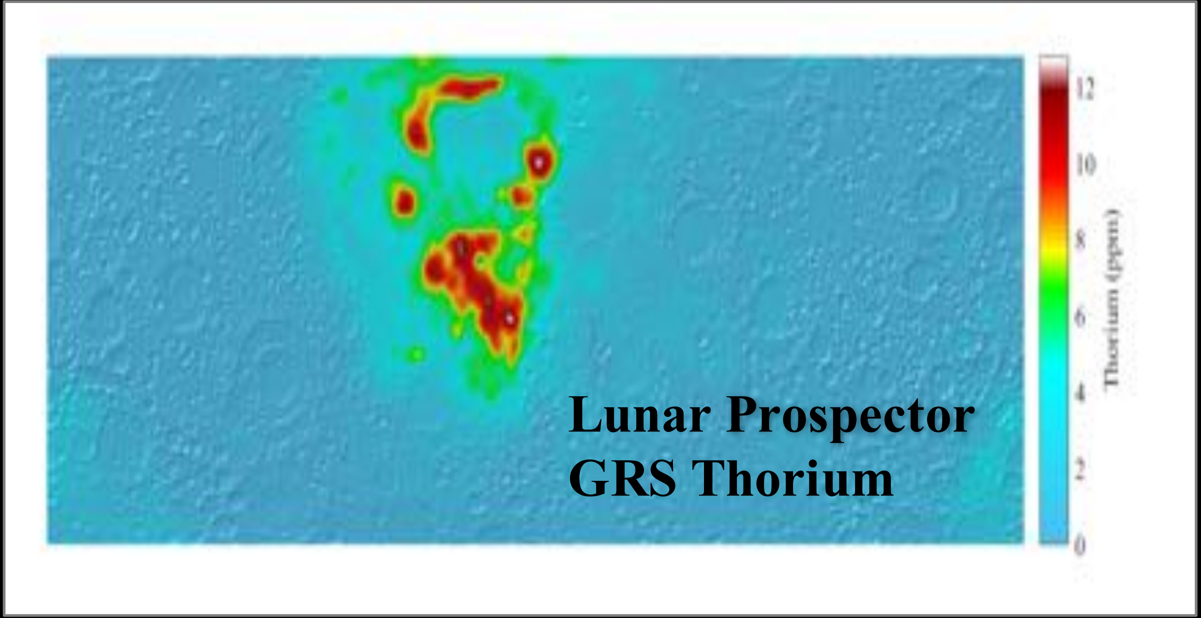


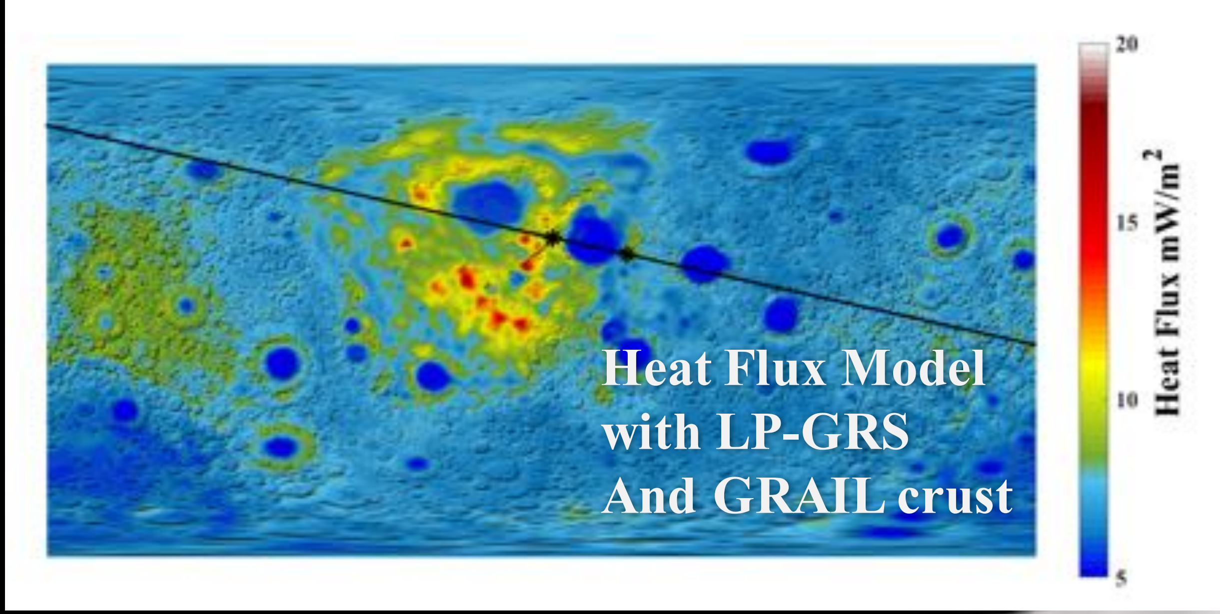


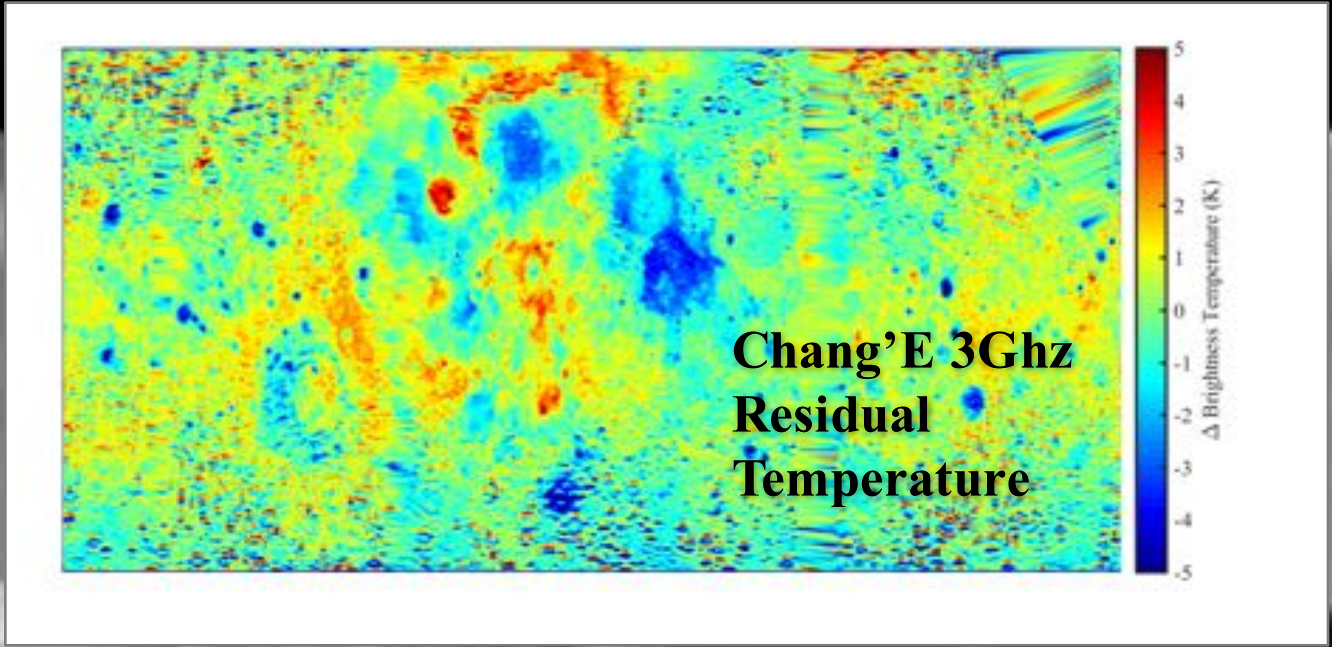
What do we see in the data?



This shows a very interesting correlation with expected heat flux…

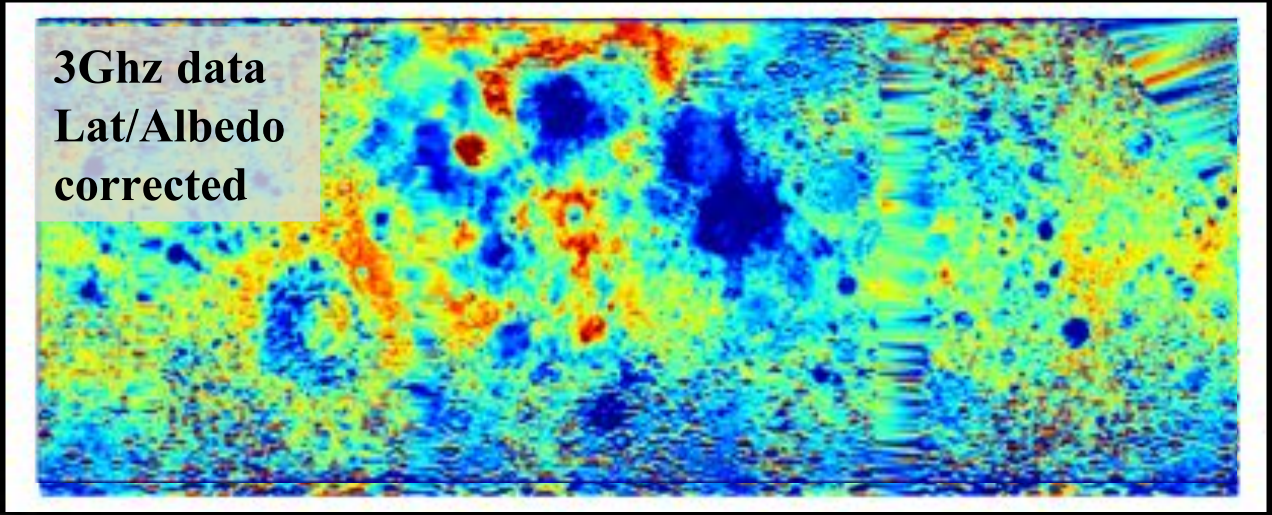


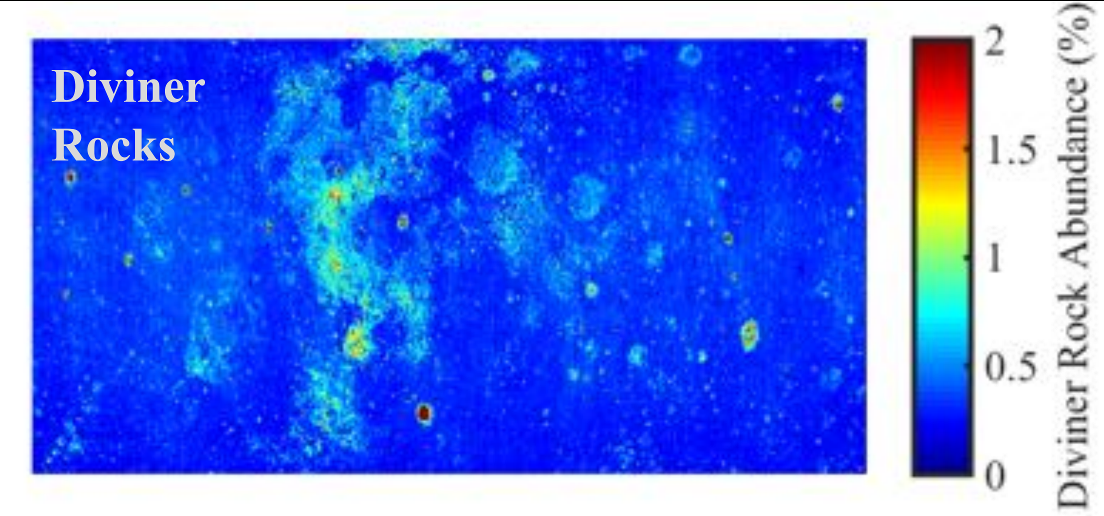


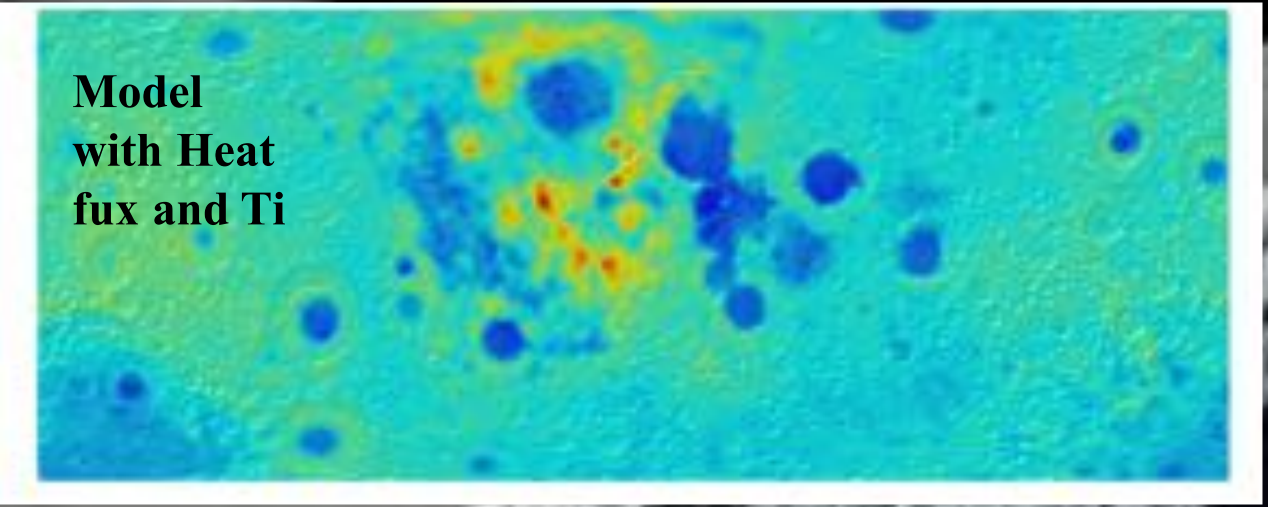


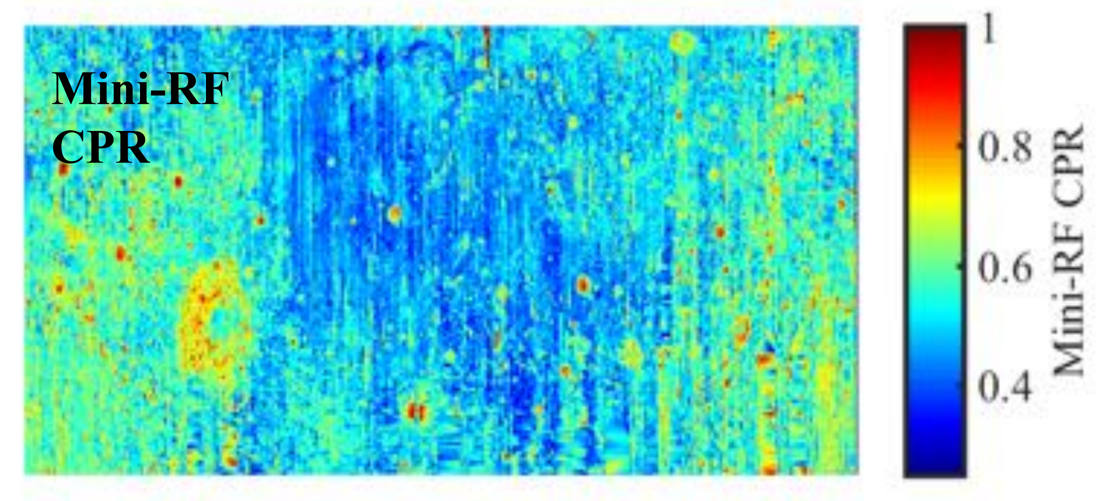
Model heat flux includes Th concentrations (and correlated U and K) from LP [Lawrence 2006 /Paige, Siegler, Warren 2016],
GRAIL crustal thickness and density models [Wieczoreck, 2013].

Which begins to show some startling similarities, but still a few major differences. These are mainly in rocky areas… and maybe Titanium correlation isn't perfect… We can try to correct for these…

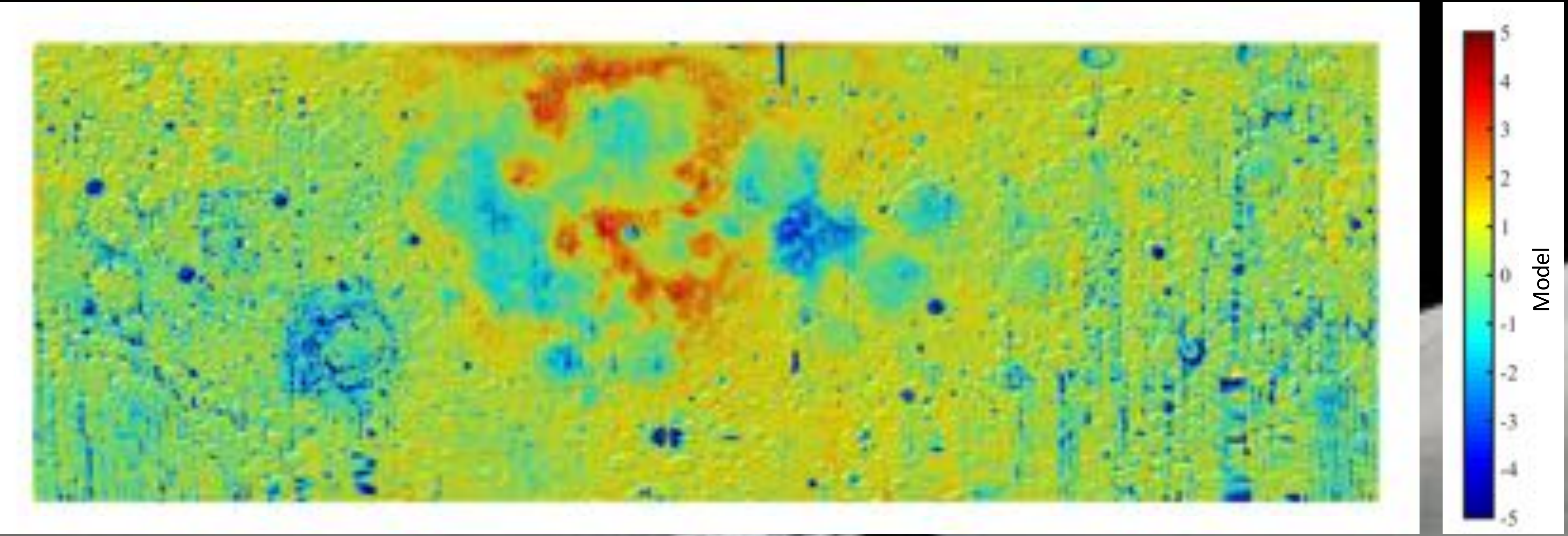






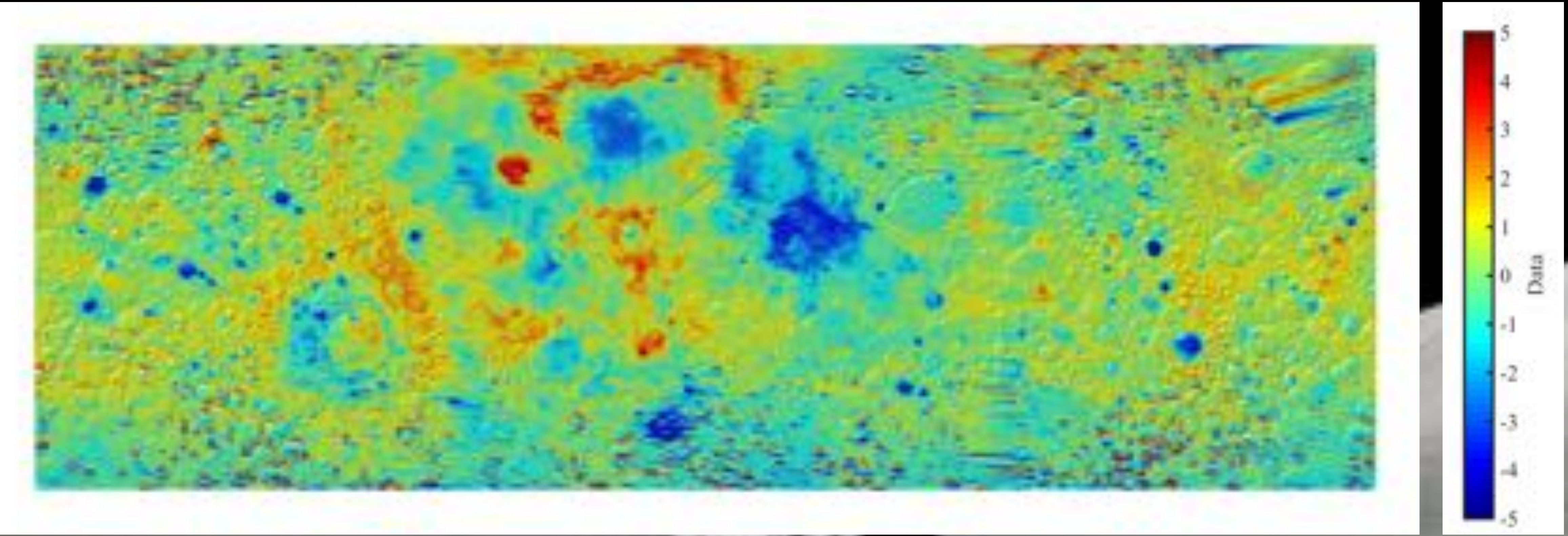


Model with "all the bells and whistles" thrown in, including subsurface rocks from CPR, etc with fits of their effect "by eye"… there isn't really much theory to go on here (e.g. how should CPR relate to loss tangent).



Model

There are certainly discrepancies, but to first order, there are some very similar features. Essentially, high-thorium, low-density regions are warmer. High titanium areas are cooler, rocky and high CPR areas are cooler.

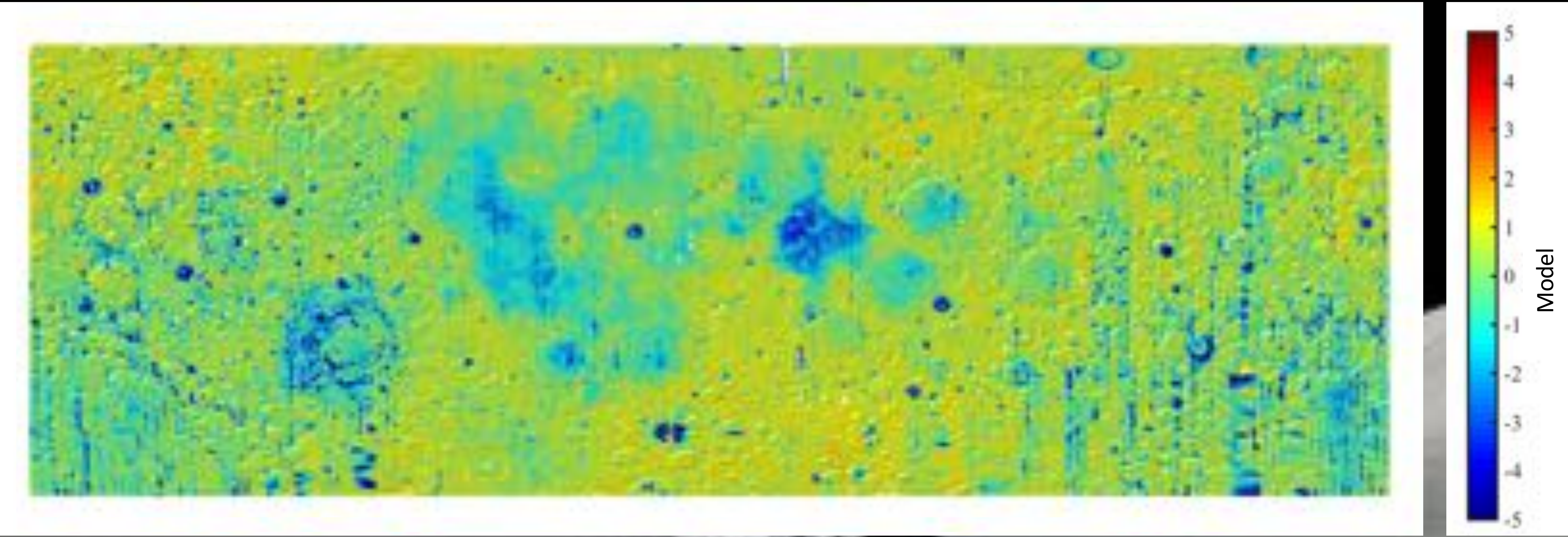


Data

Just to hammer the point home…

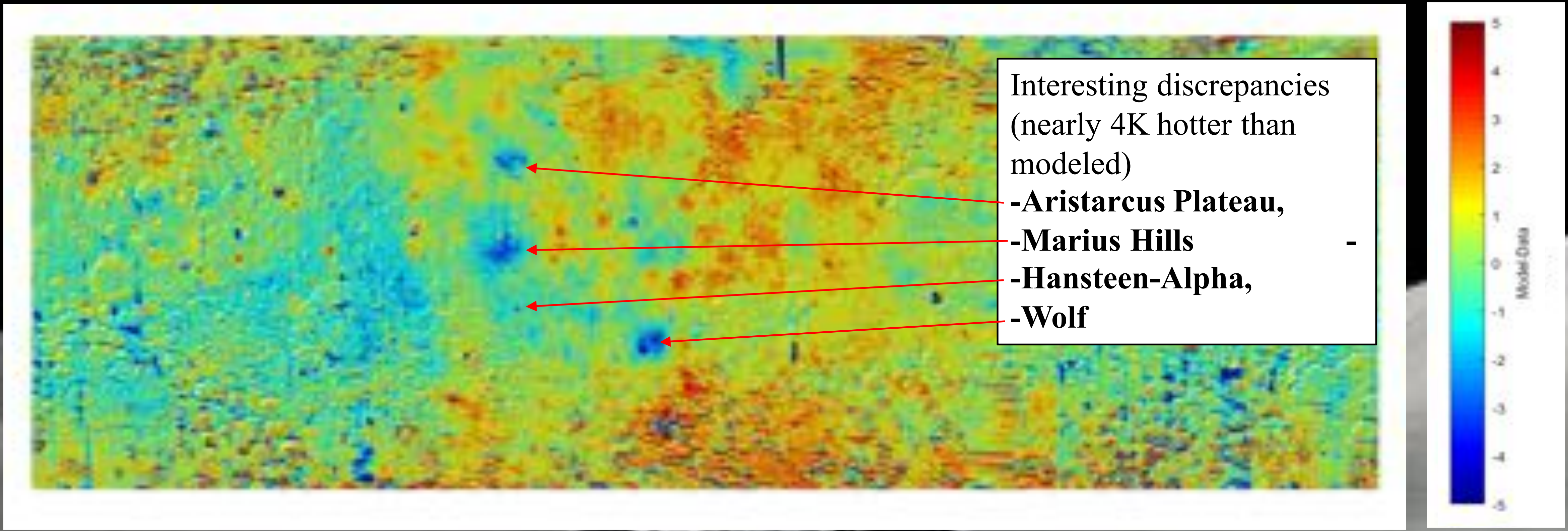
We see heat flux.

This is what the model looks like with zero heat flux (from surface Th).



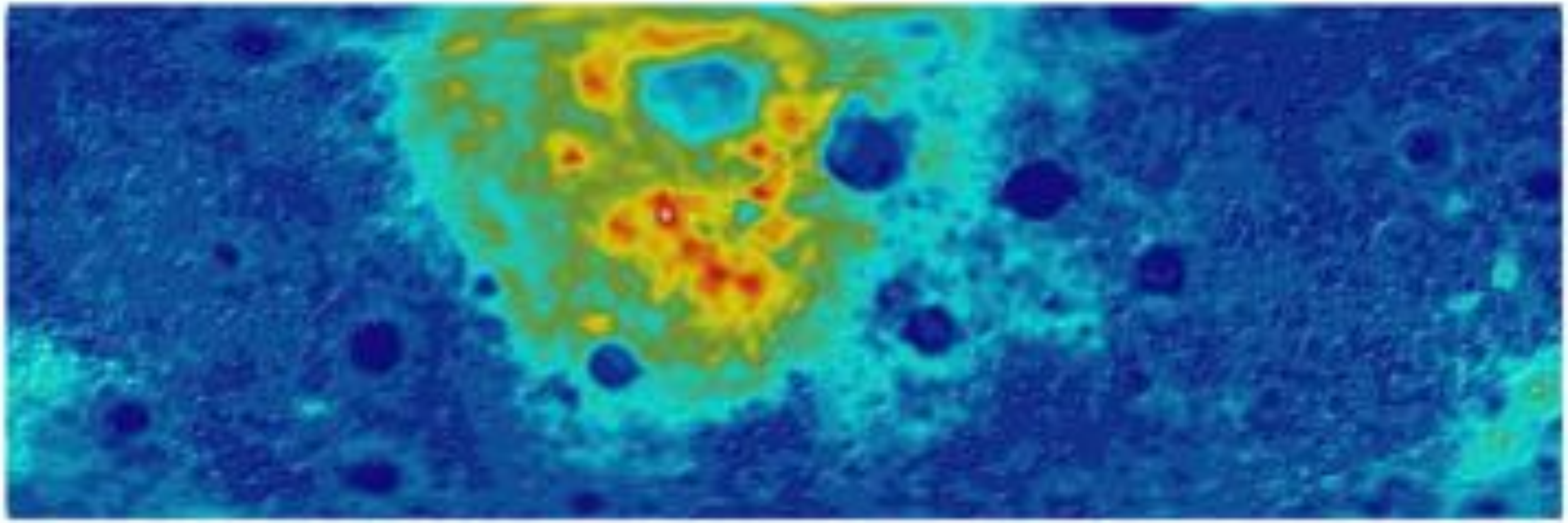
Model

There are also some interesting locations that do not show up in the model, but are hot in MRM, which could imply higher concentrations on subsurface KREEP material in these areas than would be predicted from surface Lunar Prospector measurements... These might also be interesting targets.

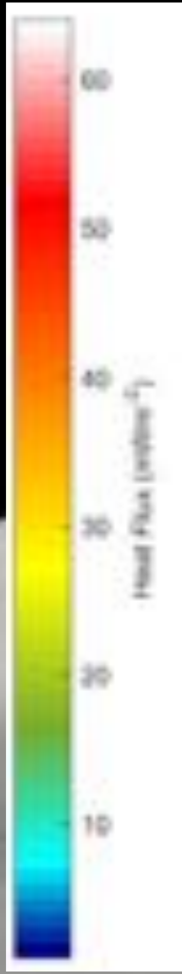


Model minus Data
(blue mean data suggests higher than expected heat flux)

All things considered, we can use the forward model to provide a best "fit" global heat flux, which can be tested again both future landed missions and potential orbital instruments like the Chang'E microwave radiometer ground based observations.



This "eyeball fit" model uses 70% surface 30% average "crust" material (e.g., Wieczorek and Phillips, 2000)



Model Heat Flux

Conclusions

- **With Apollo, GRAIL and LP-GRS data, we can create a testable global heat flux model. Landed or orbital measurements can improve the accuracy of this model.**

- **These models can be used to pinpoint the most useful landed measurement sites and can be used for "intelligent interpolation" from sparse insitu data.**

- **Orbital microwave measurement could provide a precise <u>relative</u> heat flux measurement technique, but <u>absolute</u> heat flux may not be possible (at least for MRM) and ground truth missions are likely required as ground truth (e.g. Lunar Geophysical Network, Insight).**

- **The 3Ghz (10cm) "sees" about the first 3m for highlands loss tangent assumptions -- A longer wavelength would see even deeper and therefore be more influenced by geothermal heat (1.2Ghz, 24cm => about 8m). A ~25cm wavelength lunar orbiting instrument may be able to map global heat flow and could be easily combined with an active radar instrument.**

- **We were recently funded by SSO to do new observations at Arecibo and the VLA at C, L, and P bands (~6, 21, 90cm), which should map the lunar surface at about 100km resolution. Hopefully we have neat results in a year or so.**

2.5 km thick KREEP Disc